The X –target and associated R&D needs

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Outline

- X-Target rationale and architecture
- Requirements of compression phase
- Implosion studies
- Proof of principle design
- Further studies

THE X-TARGET

In search of a simpler and more robust type of heavy ion target for IFE

A target that could be illuminated from one side with a beam array at small angles near a polar axis to facilitate thick-liquid protected chamber designs

Simple fabrication with extruded DT fill, robust RT and mix stability with very small fuel convergence ratios (~ 5 to 7)

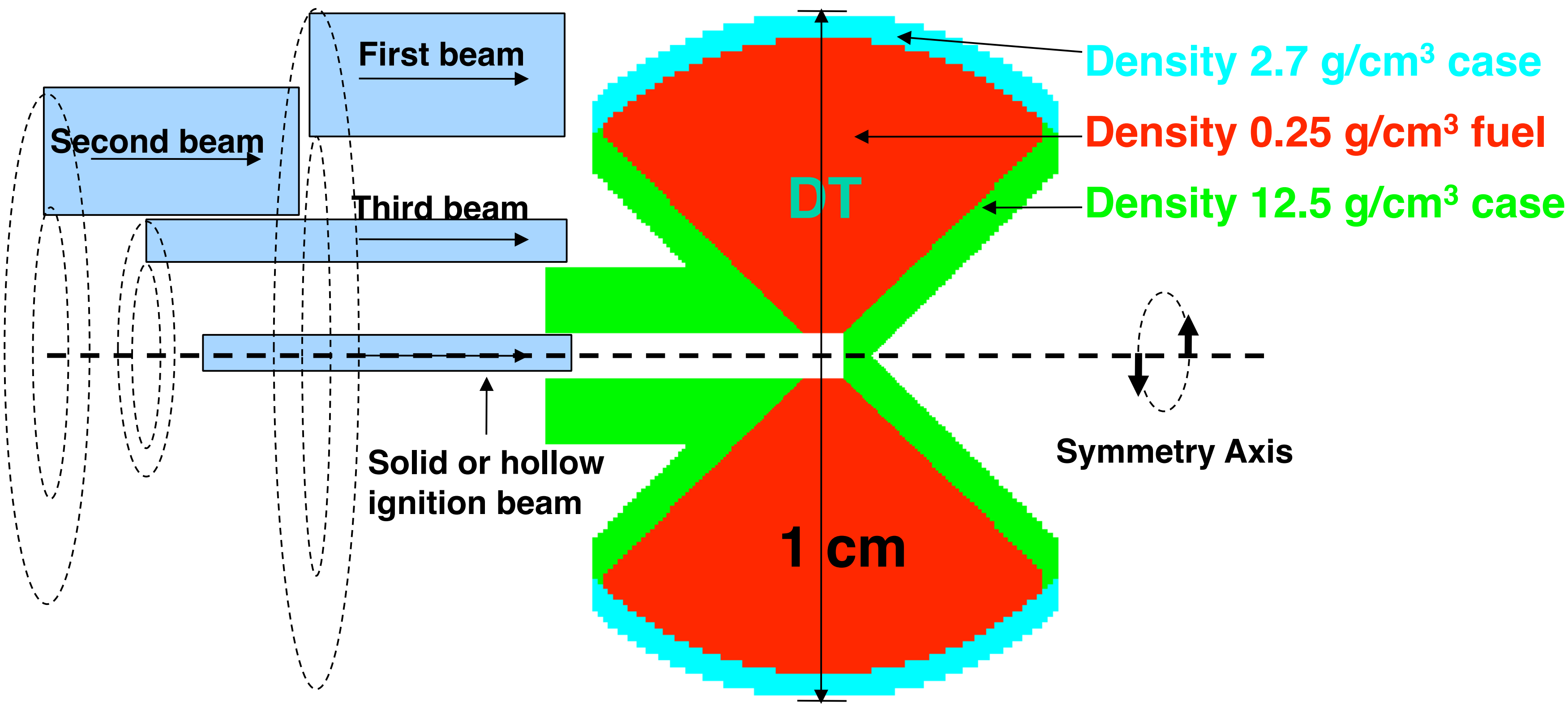
The compressed fuel should be able to be ignited with a beam of similar characteristics as the one used for compression

There is a long history of heavy-ion beam driven fast ignition and related fuel assembly (Mashke, Tabak, Callahan, Bangerter,…)

- 1-D and 2-D studies of solid and hollow ion beam ignition of preformed fuel assemblies down to 100 g/cm^3 (Herrmann, Tabak, Atzeni)
- Studies of heavy ion fast ignition and fuel assembly using single 100 GeV ion beams at ITEP (Russia)

The X-Target
HYDRA model

1^{st}, 2^{nd}, 3^{rd} and 4^{th} beams are many beams with overlapping spots modeled as annuli



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Fast ignition at low fuel densities of untampered spherical balls

HYDRA calculations of fast ignition of cold, untampered spherical balls reproduced early studies by Herrmann and Tabak, and by Atzeni

We also considered initial compressed DT fuel at densities of 30—100 g/cm^3 and ρR of 2—3 g/cm^2

For initial compressed DT fuel contained in a 300 µm radius sphere and density 100 g/cm^3:

– Yields of 1 GJ (~26% burn fraction) can be obtained using an annular or solid beam of 60 GeV uranium, ~300 kJ energy, 50 ps pulse length, and 50/100 µm inner/outer radius

For initial compressed DT fuel contained in a 400 µm radius sphere and density 50 g/cm^3:

– Yields of 750 MJ (~17% burn fraction) can be obtained using an annular or solid beam of 60 GeV uranium, ~750 kJ energy, 50 ps pulse length, and 50/100 µm inner/outer radius

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2-D implosion studies of fuel compression in the X-target

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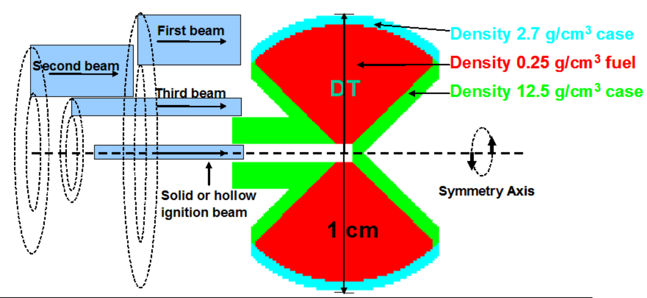


- **X-target geometry with simple DT fill, with a surrounding tamper**
- **Illuminated by axial-directed annular beams from one end**

We found that:

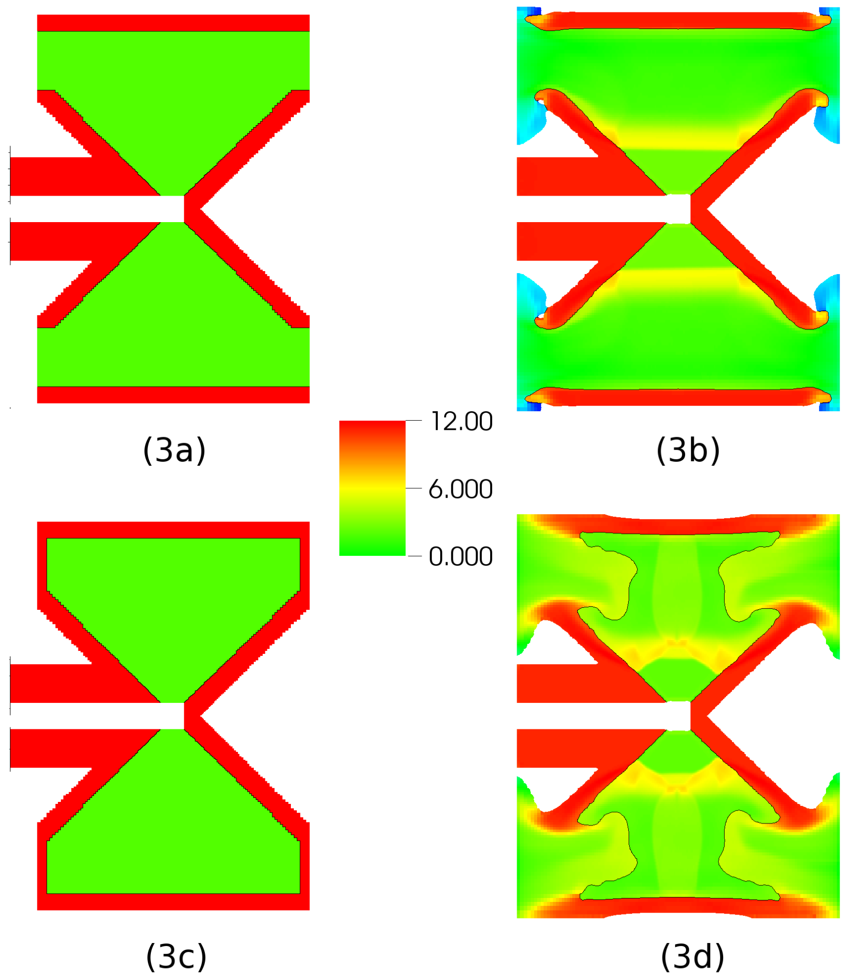
- **The axially directed heavy ion beams can compress the DT fuel radially, with quasi-3D spherical convergence**
- **The beam-heated tamper expansion can favorably affect the implosion symmetry, as the pressure in the tamper much exceeds that in the beam heated DT regions**
- **Beam deposition that explodes the entrance tamper window is approximately balanced by an equal deposition in the far end of the beam channel, thus resulting in a nearly P1-symmetric implosion**
- **Tamper motion elsewhere is minimal, and no evidence of high RT mix is seen**
- **Radiation is not an important factor to calculate the compression of the fuel**
- **Radiation is more important to properly calculate the burn propagation**

HYDRA SIMULATIONS

Example of conversion of a cylindrical implosion into a quasi-three-dimensional (hemispherical) convergent implosion

Open Case ➔ Cylindrical implosion

Closed Case ➔ Spherical implosion



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THE X-TARGET
Proof of Principle Design gets 50X gain

- **The proof of principle design uses three 60 GeV uranium beams for compression ranging in energy from 0.5 to 1.5 MJ, pulse lengths of several ns, and annular thickness of about 1 mm**
- **Other ions with equivalent range as the 60 GeV U may be used, e.g., 13 GeV K or 26 GeV Cs**
- **Our initial simulations have achieved a compression ratio of ~200, from an initial DT density of 0.25 g/cm^3 to a final density of about 50 g/cm^3 and confinement parameter ρR of about 1 g/cm^2**

- **At full compression, a third "ignition" annular or solid beam is injected through a 600 μm diameter channel**
- **This fast ignitor beam is also a 60 GeV U-beam with an energy of 3 MJ and a pulse length of 50 ps**
- **Since the channel is partially closed by the expanding case, the X-target wall tamper near the vertex is adjusted to center the Bragg peak on the midplane**

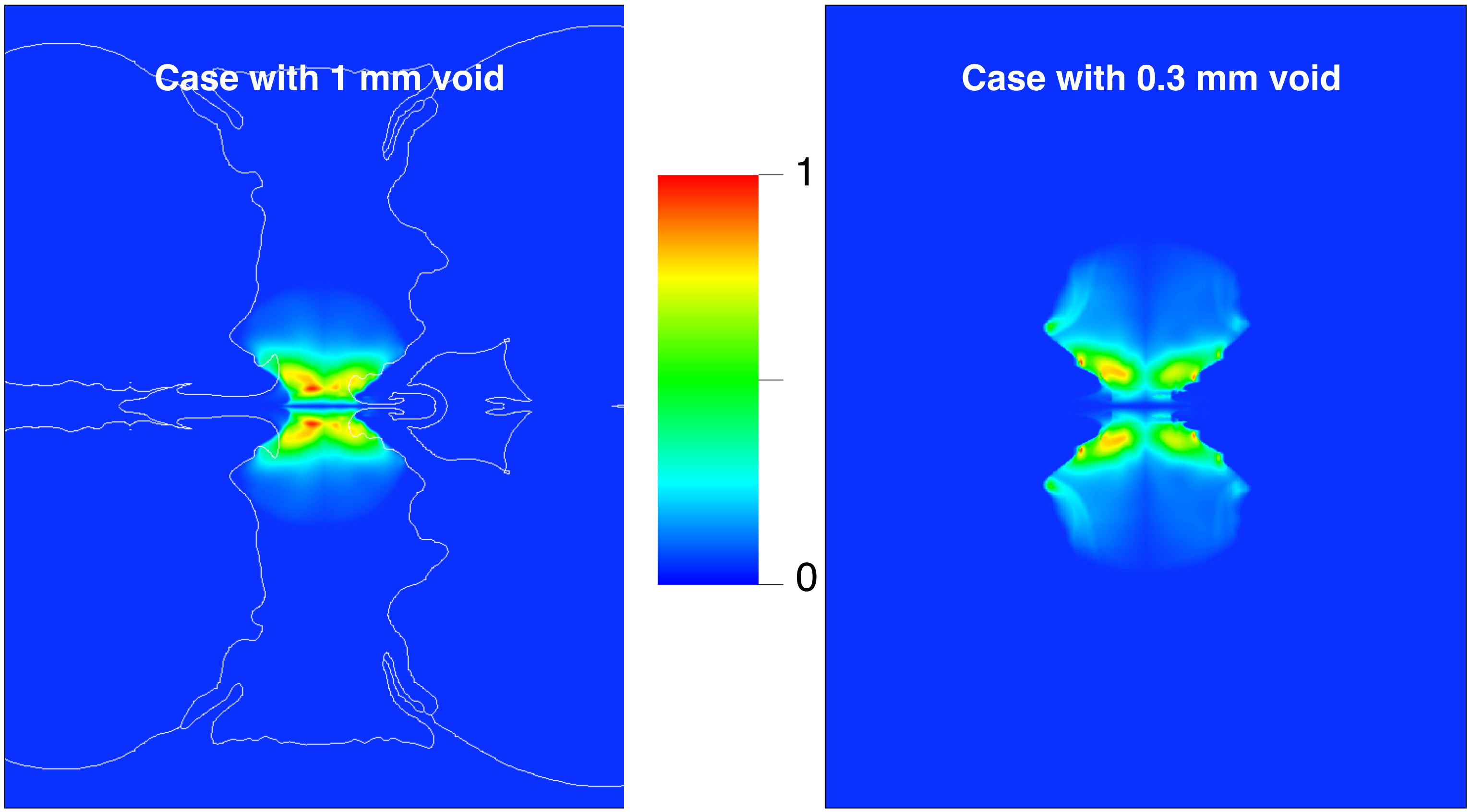
- **The X-Target requires a total beam energy of (0.5+1.5+1+3) 6 MJ and produces a yield of 300 MJ**

- **The total beam energy required to compress and ignite the present (proof of principle) target design is comparable to the energy required for the target used in the Robust Point Design**

This design has not been optimized and still represents work in progress

HYDRA SIMULATIONS

Cumulative thermonuclear energy at end of simulation



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THE X-TARGET
Further studies

LONG TERM

- Target fabrication errors, beam aiming errors and non-axissymmetric annular beams
- Preheat of DT fuel by beam halo and beam prepulse
- Beam-target interaction/Ion deposition profile
- Beam dynamics issues (longitudinal and transverse compression)
- Integrated design

SHORT TERM

- We need to achieve higher compression densities (~ 80 g/cm^3) and higher confinement parameters (ρR) to improve the burn propagation and increase the gain
- These improvements can be obtained by straightforward optimization of ion beam and tamper dynamics, e.g., an additional compression beam, optimized case geometry or stronger shocks from the third compression beam using sub-ns pulses
- 1-D analysis of compression dynamics may give us the requirements towards higher density and ρR

R&D Needs for X-target HIF→ many opportunities for collaboration

ACCELERATOR PHYSICS

- <u>Sub-ns igniter pulses</u>: *study longitudinal emittance growth limits*

  NDCX-II, and at GSI with added bunchers
- <u>Self-pinching</u>: *develop diagnostics to measure net beam currents under conditions when charge neutralization exceeds current neutralization*

  NDCX-II, RHEPP, GSI-FAIR
- <u>Stripping-induced beam emittance growth at driver scale beam perveance</u>: *measure emittance growth when stripping $Li^{+1} \rightarrow Li^{+2}$*

  NDCX-II at high currents
- <u>Dynamic gas control with multiple beams</u>: *benchmark vacuum/beam loss models*

  Rebuild 2 MV, high beam current HCX-II @ 5 Hz rep rate

TARGET PHYSICS

- <u>Hydro coupling efficiency in X-cone tampers</u>: *test compression in X-cone geometry using the beam wobbler*

  Planned @ GSI-FAIR
- <u>Study ion fast ignition</u>: *compare with radiation-hydrodynamic calculations*

  Rebuild surplus HEP/NP accelerator hardware for MJ U-igniter (cost ~ 300 M$?)

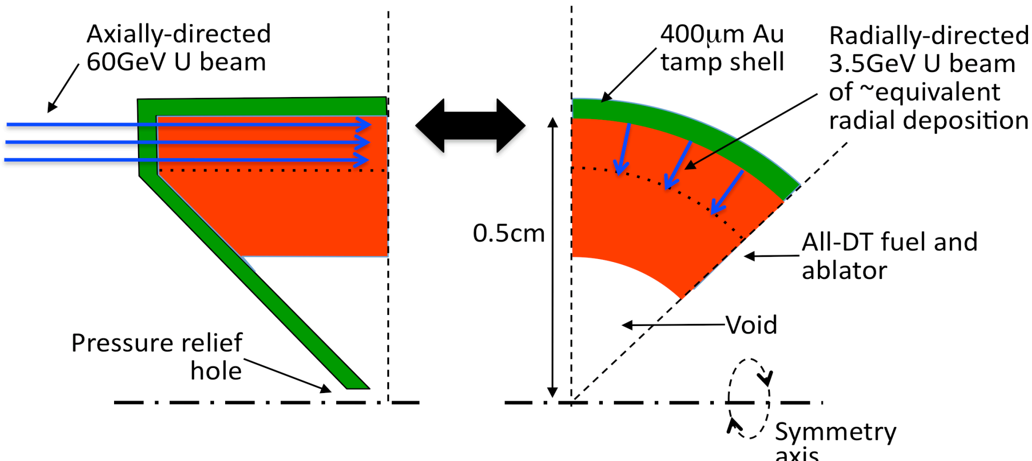
BACKUP SLIDES

1-D SPHERICAL ANALYSIS OF THE X-TARGET

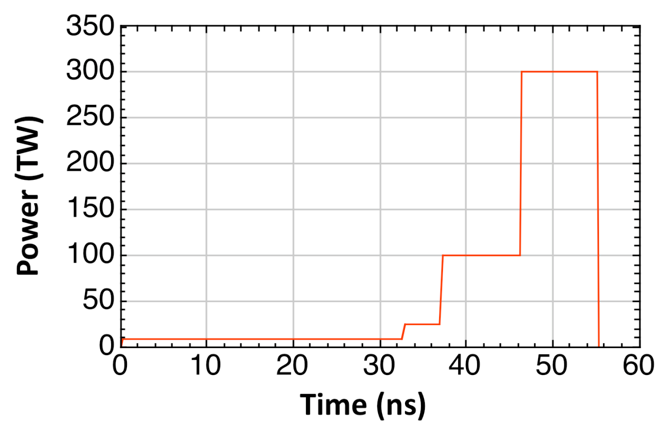
- **1-D spherical equivalent geometry of the X-target is used to determine candidate target builds and drive dynamics for higher density fuel assembly**

- **Constrained to 2 MJ total ion beam energy**
- **Ion beam power optimized to maximize the final assembled areal density**
- **A 3-shock plus main pulse, timed to synchronize shock breakout, can compress the fuel to $\rho R \sim 3.4\ g/cm^2$, average fuel density $\rho \sim 84\ g/cm^3$ and projected fusion yield of ~ 2 GJ**

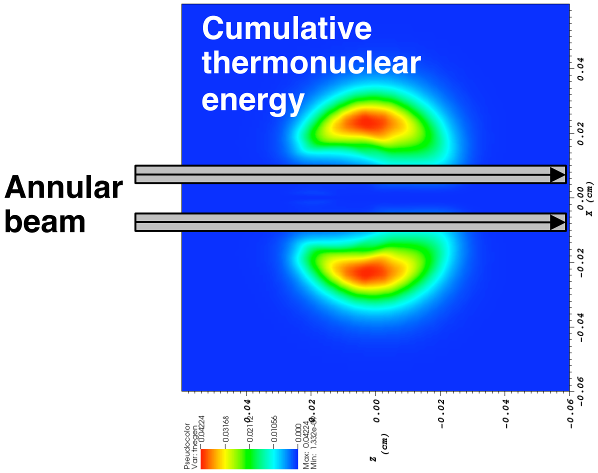
2-D | 1-D SPHERICAL | ION BEAM POWER

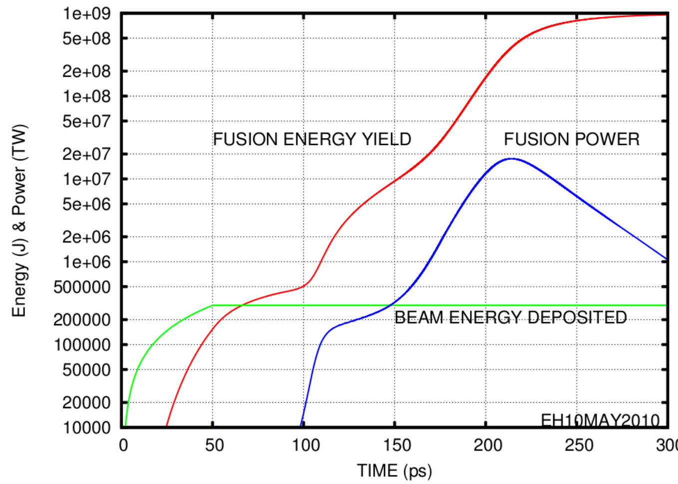


(a) X-Target (b) 1-D spherical equivalent

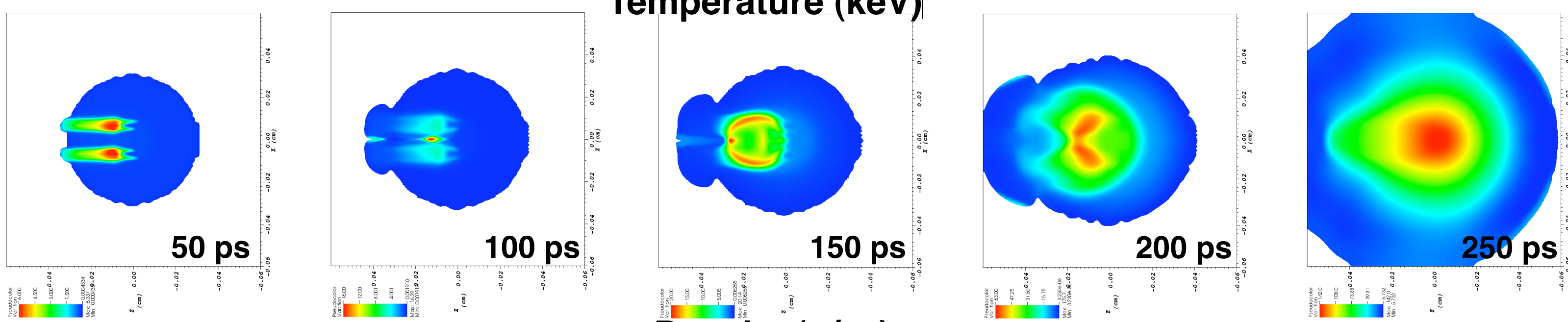


Heavy Ion Fast Ignition (HIFI) with 60 GeV U annular beam , 300 kJ, 50 ps, 50/100 μm inner/outer radius. Initial compressed fuel is a 300 μm radius sphere at temperature 200 eV and density 100 g/cm^3. Total yield is 1 GJ (~26% burn fraction)

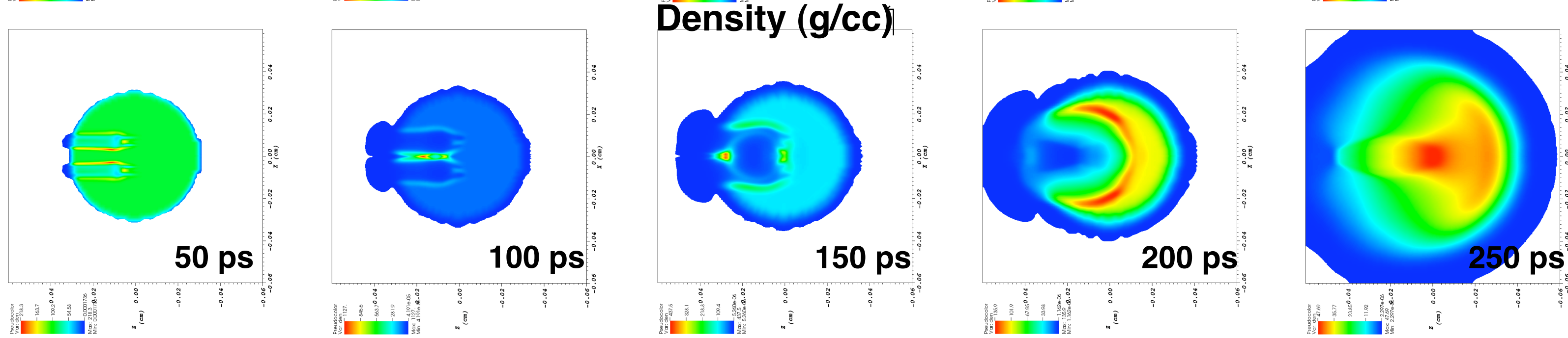




Temperature (keV)



Density (g/cc)



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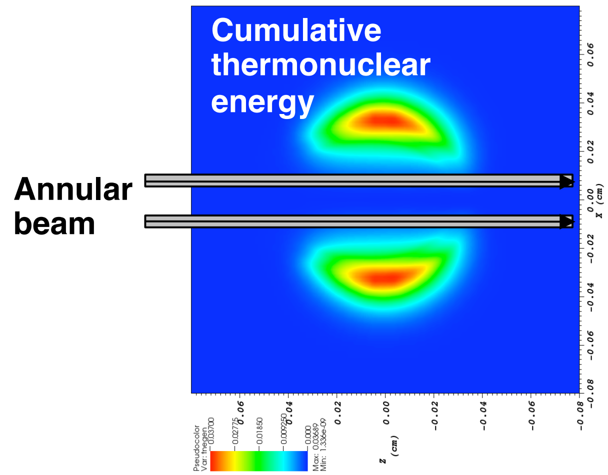
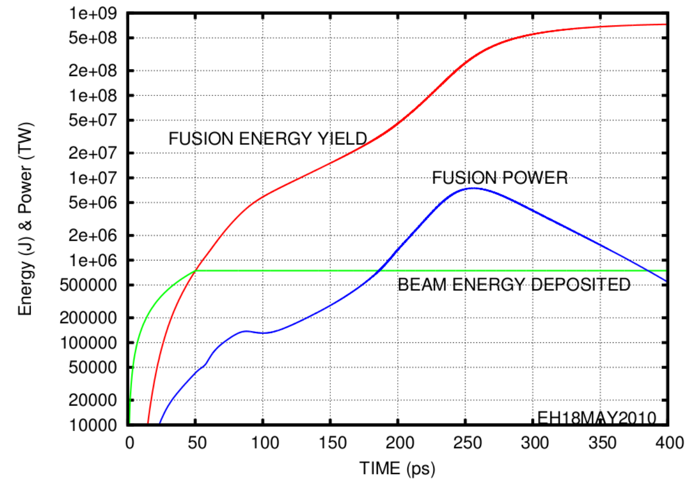
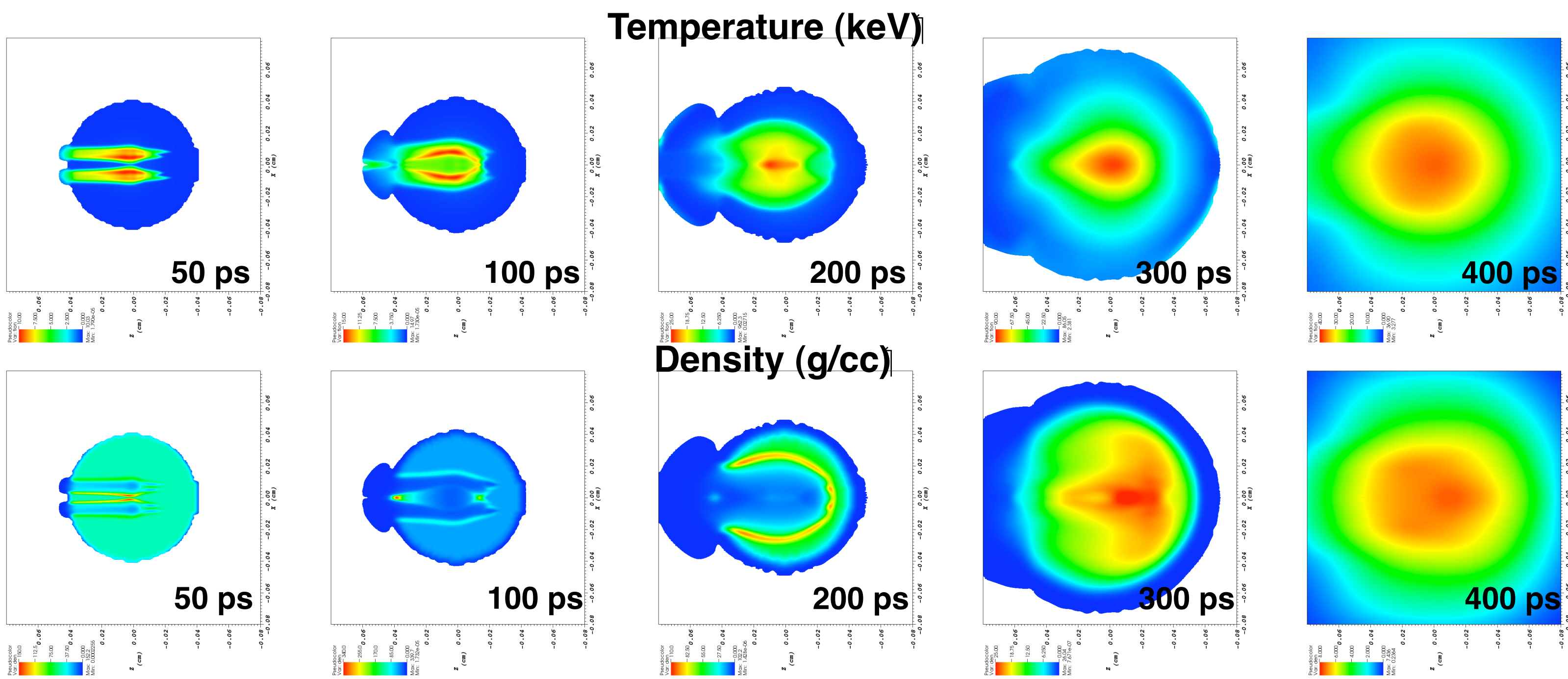


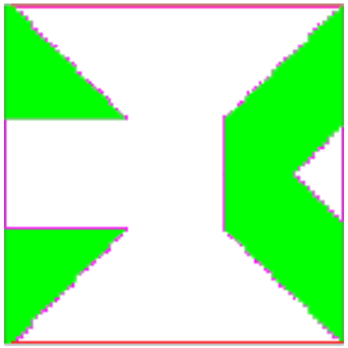


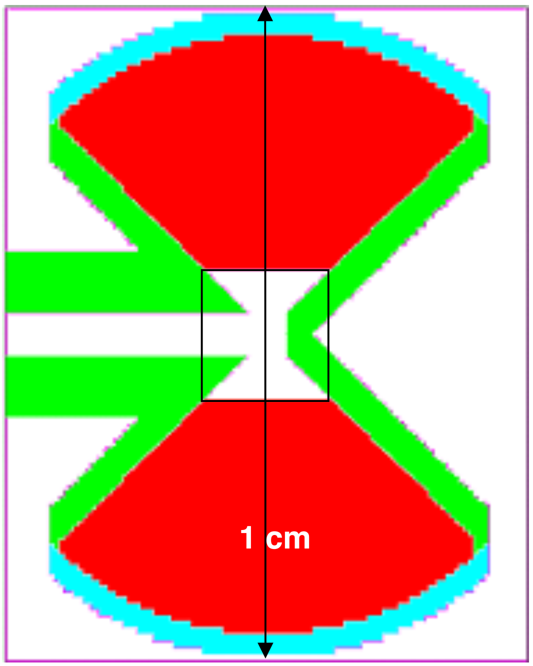


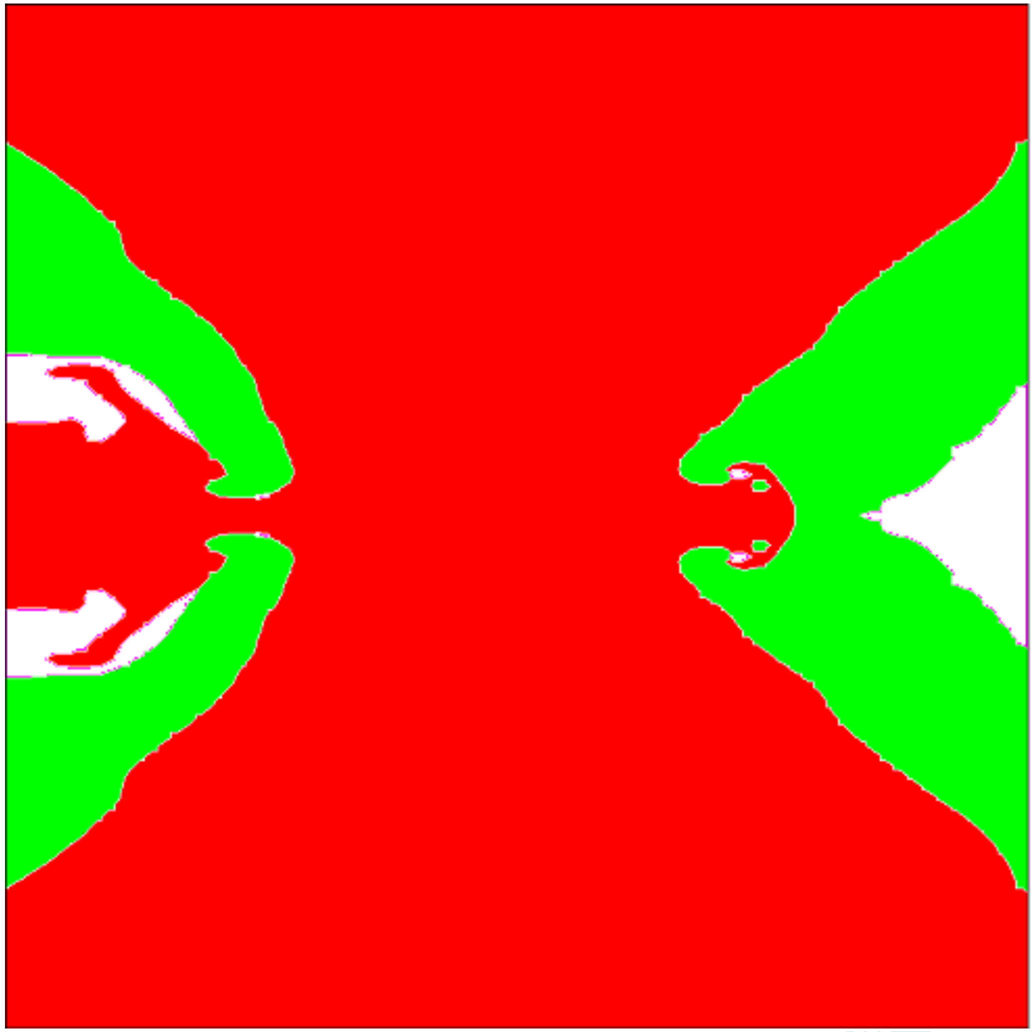
HYDRA SIMULATIONS

Material distribution at initial time and just before the injection of the ignition beam, showing very small mix effects

1X



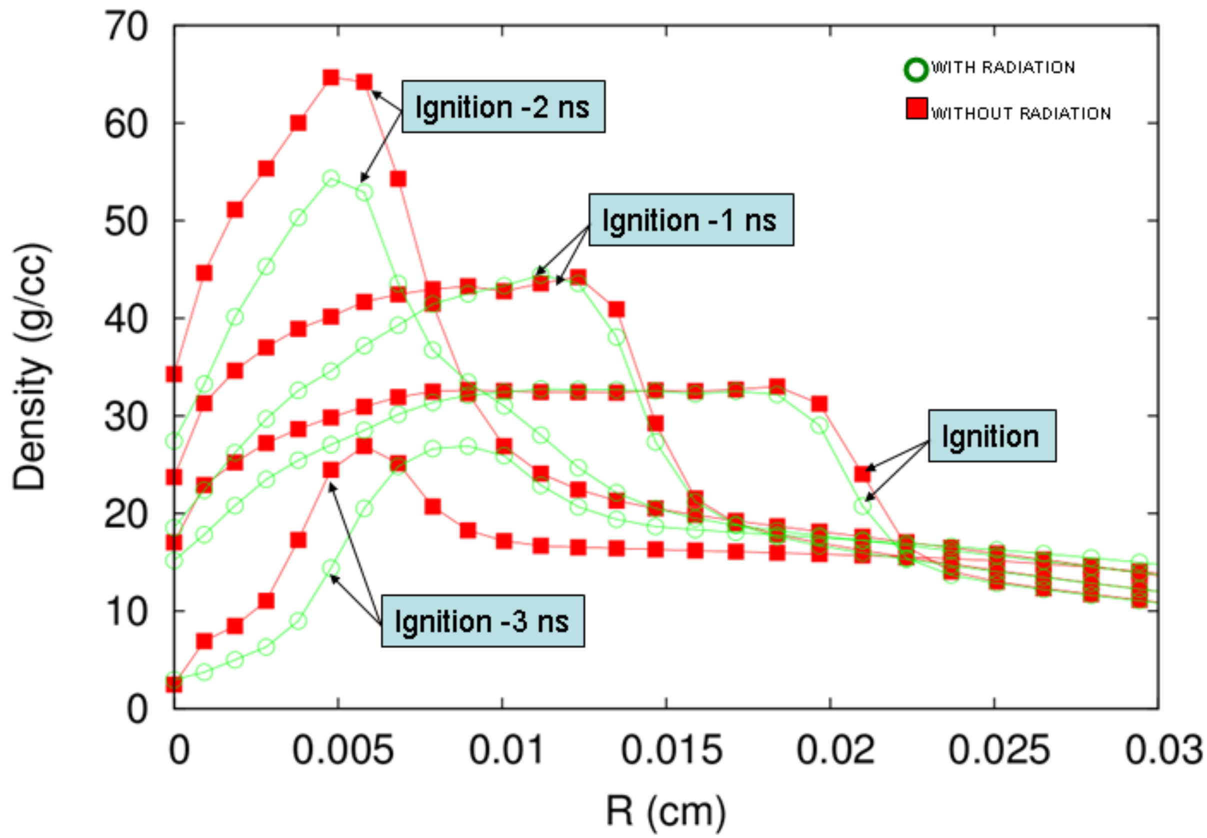




3X

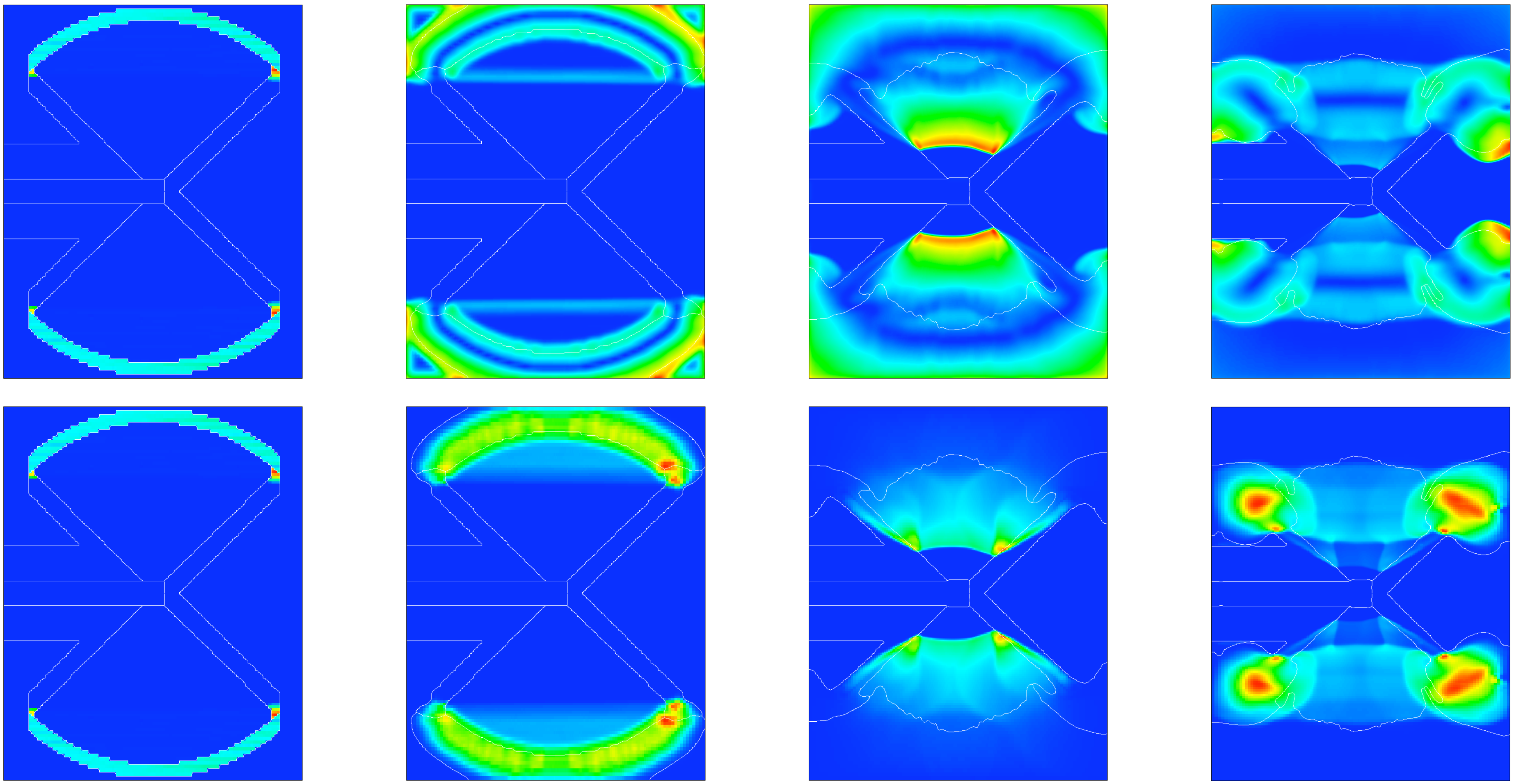
HYDRA SIMULATIONS

Radial density profiles at the midplane of the X-target as calculated by HYDRA with and without radiation at various times close to the ignition times



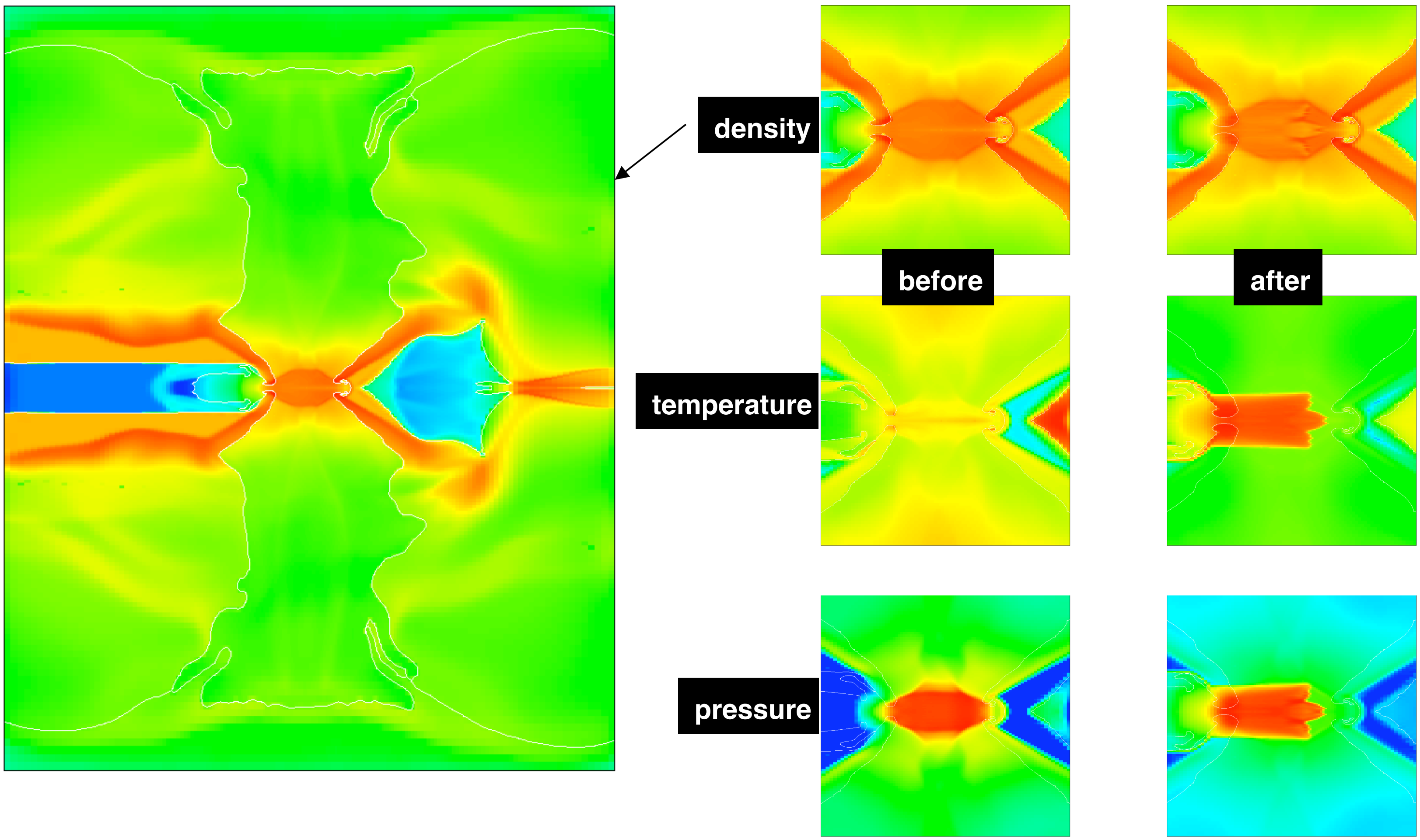
HYDRA SIMULATIONS

Fuel velocity (top) and pressure (bottom) at beginning of simulation (1 ns), at end of first beam pulse (25 ns), at start of second beam pulse (114 ns), and at start of third beam (129 ns)



HYDRA SIMULATIONS

Density, temperature and pressure at beginning and end of ignition beam pulse



The X-target potentially enhances 6-D phase space (x, v_x, y, v_y, z, v_z) admittance sufficient for fast ignition→ facilitates accelerators!

Big 1-rad focusing angle (v_x-v_y)

Big 1-g/cm² range (z-v_z)

Big 1-cm size (x-y)

→Built-in magnetic B_θ lens increases focusing angles to facilitate ignition